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An alternative experimental approach for subcritical configurations of the IPEN/MB-01 nuclear reactor

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Abstract. This work presents an alternative approach for the reactivity worth experiments analysis in the IPEN/MB-01 reactor considering highly subcritical arrays. In order to reach the subcritical levels, the removal of a specific number of fuel rods is proposed. Twenty three configurations were carried out for this purpose. The control bank insertion experiment was used only as reference for the fuel rod experiment and, in addition, the control banks were maintained completely withdrawn during all the fuel rods experiment. The theoretical simulation results using the MCNP5 code and the ENDF/B-VII.0 library neutron data are in a very good agreement to experimental results.

Keywords: Subcritical Experiment; Fuel Rods; Neutron Noise; Spectral Density.
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1. Introduction

In recent years, subcritical systems have been studied in a large scale [1,2,3,4,5,6] mainly due to the development of a new technology of subcritical reactors such as Accelerator Driven Systems (ADS) [7]. It is clear that an experimental reactivity measure becomes relevant in this context. Studies that have been carried out are focused on the development of a new and precise methodology [8].

Considering all those previously presented efforts, the aim of this work was to develop an alternative experimental approach for subcritical configurations. This alternative approach is particularly interesting due to the withdrawal of fuel rods in order to maintain the subcritical states. Based on two important procedures, which were used as reference, it was possible to estimate how many fuel rods should be withdrawal to achieve a given level of negative reactivity. The first method was the k_{eff} calculation applied to nuclear multiplying systems through the MCNP5 reactor physics code. The second method was the control bank insertion, the most traditional way for reactivity variations.

Two theoretical kinetic models were employed in this work. The first one was the point reactor kinetic model in order to determine the prompt neutron decay constant (α) [9,10]. This kinetic parameter was estimated fitting the point kinetic equation to a set of APSD (Auto Power Spectral Density) experimental data [11,12] using the least-squares method.

The second model was developed by Gandini and Salvatores [1,2] which introduces the generalized reactivity (ρ_{gen}) and the subcriticality index (ζ), a function that depends on the neutron source position and magnitude. The generalized reactivity (ρ_{gen}) is the negative reactivity worth for each step of withdrawing fuel rods of this work. The proposed alternative method relies only on measured quantities, as counting rates of detectors.

2. Methodology

The proposed alternative experiment was implemented in the IPEN/MB-01 reactor and was simulated employing the MCNP5 code. Control bank experiments have an already well-known behavior [13] and, due to this fact, it was used only as reference for fuel rod experiments. The control banks method is the conventional way to study the system reactivity; controlling neutron population trough the insertion or withdrawn of control banks (simultaneously/separately) in the core active region depending on the specific range of interest. Twenty-three subcritical configurations were developed in this work.

The design of these twenty-three cases was developed employing MCNP5 based on the IPEN/MB-01 reactor geometrical structures and isotopic materials concentration. The characterization and determination of each material of the reactor is very important to obtain precise results and a good accuracy with the real experiment.

Criticality calculations performed by MCNP5 were carried out using the KCODE criticality source card. This card provides the possibility to calculate the multiplication factor, which is a ratio between two consecutive generations of neutrons and can be able to sustain a chain reaction by fission neutrons; it is characterized by k_{eff}, e.g., the eigenvalue to the neutron transport equation [10].

The way to calculate the k_{eff}, in the MCNP5, is using an estimating of the mean number of fission neutrons produced in one generation per fission neutron started. The generation can be interpreted as the life of a neutron from “birth” in fission to “death” by escape, parasitic capture, or absorption leading to fission. The computational calculation of the fission generation could be denoted by a k_{eff} cycle, which is a computed estimate of an actual fission generation [14]. The control banks k_{eff} values were used to estimate the number of fuel rods that is necessary to withdraw from the core. It was also possible calculate the fuel rods k_{eff}, and an approximated value to the subcriticality level could be achieved.

The experiments were based on the 26 x 24 fuel rods core configuration instead of the standard 28 x 26 fuel rods configuration. The total number of fuel rods for this new core configuration was 576 and provides practically zero excess of reactivity, therefore, the criticality can be reached with all the control banks withdrawn. In this way, it is possible to achieve large range of subcritical levels using this configuration. The removal of fuel rods started by the peripheral region due to its low negative reactivity worth and from the north and south faces of the core matrix. The east and west faces were left unchanged due to the presence of the experimental detectors and the external neutron source, respectively. Particularly, the number and the position of the fuel rods in the column in front of the detectors were kept unchanged to avoid any neutron flux distortion in this area and not impair the detectors measurements. The additional external neutron source of Am-Be of 1 Ci (strength 2.6×10^6 neutrons/s) was employed in order to improve the statistics of the detectors’ counts, and so the resolution of APSD´s. This neutron source was placed in the middle of the active region, between rows 14 and 15 and leaning against these two fuel rods as shown in Figure 1.

The advantage of maintaining the control banks totally withdrawn during all the fuel rods experiment is to avoid local neutron flux depression caused by control banks insertion, which depresses the neutron flux in its vicinity inducing a subsequent shadowing between the two control banks. This shadowing effect is very difficult to be taken into consideration in calculation methods.

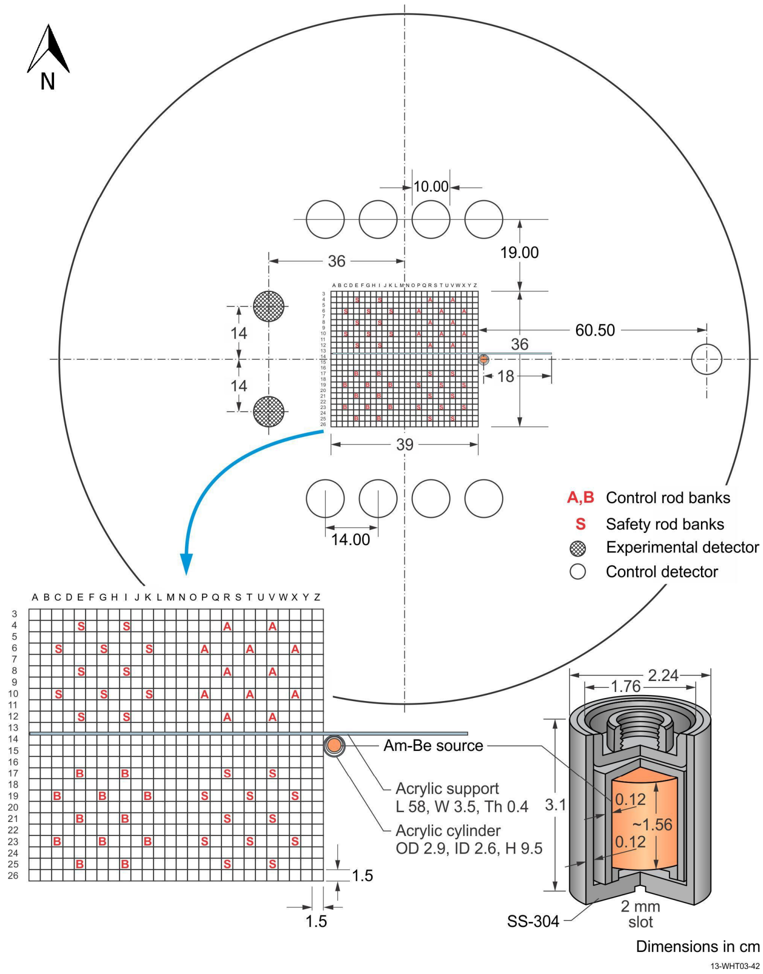

Figure 1 - Upper View of the Core of the IPEN/MB-01 Reactor. The neutron source position, the control and safety rod banks, the experimental and control detectors are represented in this figure.

The Am-Be source was installed inside of an acrylic cylinder and it was disposed in an acrylic support. Furthermore, the neutron source was used only in the experimental procedure because of the KCODE card does not allow to implement this condition during computational simulation and also subcritical systems require an external source to maintain a steady state. The first and the last core configuration can be seen, respectively, in the figures 2 and 3.

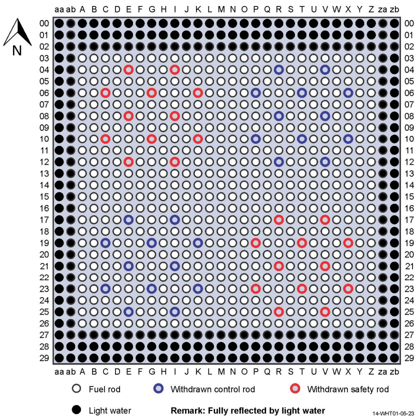

Figure 2 - Core Configuration for Case 1

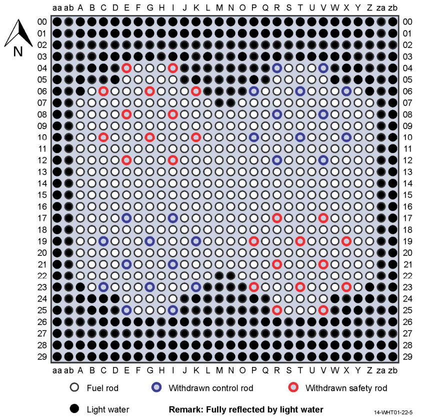

Figure 3 - Core Configuration for Case 23

Through the point reactor kinetic equations and using standard procedures [10,15], the APSD of the neutron noise was described considering the standard electronics chain, for a pulse-mode detector, and the zero-power transfer function. Moreover, the prompt neutron constant decay (α) was obtained using the following equation:

$$\Phi(\omega) = \frac{A}{\omega^2 + \alpha^2} + C \tag{1}$$

where ω is the angular frequency, A and C are constants, being C the uncorrelated or detector noise, and Φ is the APSD to fit to the experimental data.

The generalized reactivity (ρ_{gen}) developed by Gandini and Salvatores [1,2,12] kinetic model can be expressed by the Eq. (2).

$$\rho_{\text{gen}} = (\alpha l_{eff} + \beta_{eff})(1 - P_N) \tag{2}$$

where α is obtained by the Eq. (1), l_{eff} and β_{eff} are parameters obtained from previous works [16], and P_N is the relative power of two consecutive states By analogy with the point kinetic model, the power for a certain state is given by: [11,17]

$$P = \frac{2R^2(\gamma D)l_{eff}^{-2}}{(B)^2(\Phi^p - C)} \tag{3}$$

where,
R is the average count-rate of the pulse mode detectors,
$\gamma$is the energy released per fission in Joule,
D is the Diven factor [17] given by: $<\nu(\nu-1)>/<\nu>^2$, where ν represents the number of neutrons emitted per fission, and the brackets represents the average value,
B is the prompt neutron decay constant α or its analogue, depending on the kinetic model employed,
$\Phi^p =$ mean value of the APSD on the first plateau level in V^2/Hz for current mode detector, or Counts^2/Hz for pulse mode detector,
C = mean value of the plateau of the uncorrelated noise.

Now, considering two consecutive states *a* and *b*, which *b* is more subcritical than *a*, and assuming that l_{eff} is independent of the subcriticality levels, the relative power between these two states can be written as:

$$P_N = \frac{P_b}{P_a} = \frac{R_b^2 \, B_a^2 \, (\Phi_a^p - C_a)}{R_a^2 \, B_b^2 \, (\Phi_b^p - C_b)} \tag{4}$$

Thus, through Eq. 2 the parameter ρ_{gen} can be obtained in a purely experimental way. The multiplication factor, k_{eff}, is obtained as: $k_{eff} = 1/(1-\rho)$, where ρ is the total reactivity.

The measurements start with the two control banks completely withdrawn. Then, specified numbers of fuel rods were removed from the core in carefully chosen steps. In each of these subcritical states; the APSD, the counting rates of the detectors used, and the temperatures were measured. The inferred quantity of interest in this evaluation is k_{eff} which is obtained as $1/(1-\rho)$ where ρ is the total reactivity; i.e., the sum of partial ρ_{gen}.

3. Results

Table 1 shows the MCNP5 simulated and measured values of the multiplication factor (k_{eff}) for the fuel rod experiment. It must be emphasized that all the control banks were maintained totally withdrawn from the core during the fuel rods experiment.

The MCNP5 simulations for fuel rods were run with 4050 cycles with 60000 neutron histories each. The first 50 cycles were skipped. The calculated results of configurations 1 through 21 are within 1σ range of the uncertainty of the measured value, while the one of configuration 22 is within 2σ range of the uncertainty of the measured value. The calculated result of configuration 23 is outside the 3σ range.

The uncertainty in the final value of k_{eff} for each configuration is the result of a combination of experimental uncertainties derived from acquired data and those arising from geometrical and material composition data; the latter were evaluated by computational codes.

Table 1 – The k_{eff} for the fuel rods simulation realized by the MCNP5 and its measured results.

Configuration	**Fuel Rods**	**Empty Positions**	**Measured results** $k_{eff} \pm \sigma_k$	**MCNP5** $k_{eff} \pm \sigma_k$
1	576	276	1.0004 ± 0.0006	1.0007 ± 0.0002
2	564	288	0.9987 ± 0.0006	0.9991 ± 0.0002
3	560	292	0.9979 ± 0.0006	0.9983 ± 0.0002
4	556	296	0.9973 ± 0.0006	0.9976 ± 0.0002
5	550	302	0.9960 ± 0.0006	0.9964 ± 0.0002
6	546	306	0.9949 ± 0.0006	0.9952 ± 0.0002
7	542	310	0.9938 ± 0.0006	0.9942 ± 0.0002
8	536	316	0.9926 ± 0.0006	0.9924 ± 0.0002
9	532	320	0.9912 ± 0.0007	0.9912 ± 0.0002
10	524	328	0.9899 ± 0.0007	0.9898 ± 0.0002
11	516	336	0.9879 ± 0.0007	0.9876 ± 0.0002
12	510	342	0.9859 ± 0.0007	0.9860 ± 0.0002
13	508	344	0.9842 ± 0.0007	0.9837 ± 0.0002
14	499	353	0.9814 ± 0.0008	0.9814 ± 0.0002
15	493	359	0.9791 ± 0.0008	0.9790 ± 0.0002
16	486	366	0.9762 ± 0.0008	0.9762 ± 0.0002
17	481	371	0.9746 ± 0.0009	0.9740 ± 0.0002
18	471	381	0.9708 ± 0.0010	0.9712 ± 0.0002
19	460	392	0.9659 ± 0.0010	0.9668 ± 0.0002
20	456	396	0.9623 ± 0.0010	0.9624 ± 0.0002
21	446	406	0.9583 ± 0.0010	0.9578 ± 0.0002
22[a]	444	408	0.9548 ± 0.0010	0.9529 ± 0.0002
23[a]	444	408	0.9522 ± 0.0011	0.9475 ± 0.0002

[a] Configurations 22 and 23 have the same number of fuel rods, but the geometry is different.

The experimental uncertainties in the k_{eff} are the ones arising from the measurements of reactivity given by experimental approaches and from measurements of the average temperature given by thermocouples. The measured reactivity of the first configuration carries uncertainty components due to uncertainties of kinetic parameters used in the reactivity meter. This uncertainty was evaluated as follows.

The detector signals that gave rise to the reactivity determination were recorded. The reactivity meter was then run twice. In the first run all kinetic parameters, effective delayed neutron fraction, β_{eff}, the prompt neutron generation time, l_{eff} , the delayed neutron decay constant, λ_i, and the delayed neutron abundances, β_i, were increased by adding to their values the uncertainty on these basic parameters. The second run was the opposite. All kinetic parameters were decreased by subtracting from their values the uncertainty on these basic parameters. The reactivity meter reactivity uncertainty, only for configuration 1, was then taken to be equal to the difference of these two reactivity determinations. The reactivity uncertainty due to the uncertainty of the kinetic parameters was found to be much smaller than the statistical uncertainty of the reported reactivity (10pcm ± 3 pcm) [18].

Now, considering the subcritical configurations, the uncertainty of the measured reactivity, ρ_{gen}, already takes into account the measurement uncertainties and the uncertainty of the kinetic parameters l_{eff} and β_{eff} used in the approach. Equations 2 and 4 show that explicitly.

In the last step (configuration 22 and 23) shown in the figure 4, the difference value of -474pcm between the simulated and experimental subcritical reactivity may be seen and could be explained as the statistical resolution of the detector in this very subcritical state. In high levels of subcriticality, more sensitivity detectors should be employed.

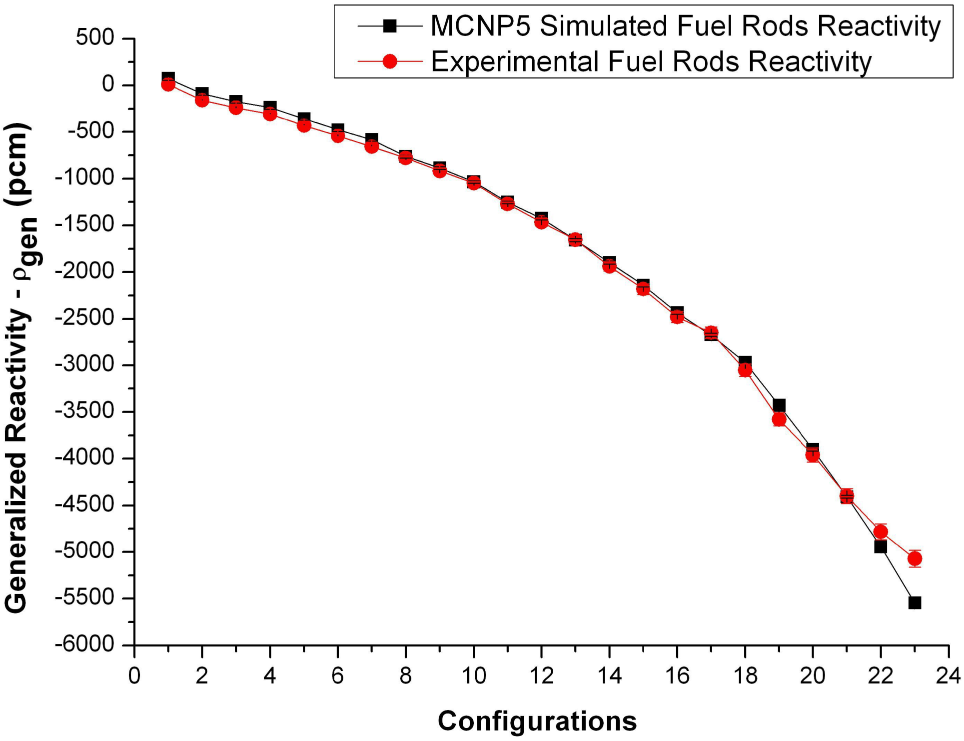

Figure 4 –The generalized reactivity (ρ_{gen}) fuel rods measured and simulated result values obtained through the Gandini and Salvarotes kinetic models and MCNP5, respectively.

4. Conclusions

The new experimental approach using fuel rods withdrawn was successfully accomplished in the IPEN/MB-01 reactor and it was possible to obtain a good accuracy of the parameter ρ_{gen}. The comparison between simulation and experiment shows good agreement, except for the configuration 23, where it is believed that the detector lost a statistically reliable response.

This work can be considered relevant in the subcritical study context since it introduces a new method to achieve subcritical reactivity levels in an alternative and well-success way.

For future work, an additional subcritical configuration could be done using boric acid diluted in the whole tank of water of the moderator/reflector. Furthermore, a study is already being done for the feasibility of use of an input logic nuclear module for data acquisition with which will be possible to make logic operations with the neutron signals from two or more detectors and improve the statistical resolution in very subcritical configurations. Also, a more complex and detailed study of the neutron flux will be developed employing the mesh tally through the MCNP5.

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